Modelling the future: a joint venture

David Rind, Arthur Rosenzweig and Cynthia Rosenzweig

The consequences of a possible global warming are far from clear. Modellers of economic and climatic change need to put their heads together.

DURING the autumn of 1987, two events occurred which highlighted our inability to forecast near-term anomalies. First, on 15–17 October an intense storm moved through western Europe, the strongest storm in the area for over a century. Hurricane-force winds disrupted electrical power and transport across southern England, and sea-level pressure in London dropped to 960 mb, the lowest on record. High winds and heavy flooding were experienced from Spain to Scandinavia[1].

Then, some three days later, on 19 October the share prices of publicly traded American corporations as measured by the Dow Jones Industrial Average of thirty leading stocks dropped by roughly 500 points, or more than 20 per cent of total value. About 500 billion dollars were wiped off the slate. By all methods of accounting, it was the greatest asset 'melt-down' in financial history.

In addition to the proximity of these events in time, they have one other thing in common: in neither case was such an extreme occurrence forecast, and even during the events, meteorologists and economic analysts were incapable of keeping up with the rapid changes. The inability to foresee these extreme anomalies has properly raised doubts about how well experts in the two fields understand their subject, especially when dealing with situations outside the norm.

Electronic computer

Both atmospheric and economic modelling became practicable with the advent of the electronic computer after the Second World War. John von Neumann, the computer pioneer, saw meteorology and economics as the two applied sciences which could most benefit from the power of computers because of the size and complexity of their models[2]. In recent decades, numerical forecasting in the two disciplines has proceeded with varying degrees of success, and without much interaction between them. Now, however, climate and economic modellers will have to combine to tackle a new forecasting problem: the effects of climate change on world economies.

Increasing concentrations of greenhouse gases in the atmosphere are expected to produce significant alterations in Earth's climate over the coming decades[3,4] (Fig. 1, see over). Although researchers have focused on the problem of predicting what the climate changes will be, and to a lesser extent on estimates of future trace gas releases, so important to climate projections (Fig. 1), these efforts have not been interactive. Furthermore, analysis of the consequences of such changes for society lags far behind. In recognition of this deficiency, the World Meteorological Organization has called on governments to increase their support for analyses of the possible economic effects and appropriate policy options[5]. The Congress of the United States has asked the US Environmental Protection Agency to report on the potential effects of climate change and the possibilities for stabilizing climate. In response, the agency has initiated a programme which includes linking climate models with economic models. The results are due this autumn.

There are at least 20 global simulation models in use in each of the two disciplines, with less than half of the atmospheric models being used for long-term climate-change assessment. Are climate and economic models compatible? What are their respective strengths and weaknesses? Can we have any confidence in their joint prediction of the effects of climate change in the next century, when they cannot foresee record-breaking events that happen the very next day? We will address these questions through a comparison of the two modelling approaches, and suggest ways in which the disciplines can begin to work together.

The most striking difference between climate and economic models is in the relationship of the models to the basic principles of the disciplines. Climate forecasters use 'general circulation models' which solve the fundamental equations representing the well-established theories of conservation of physical quantities (mass, energy, momentum and moisture). At least ideally, they are operating directly from these first principles. For example, in order to forecast the coming climate change, a modeller increases the amount of CO_2 and other trace gases in the radiation scheme; this reduces the amount of energy leaving the atmosphere, which in turn alters the temperature and then other climate variables in the model such as winds, cloud cover and precipitation patterns. All that modellers require to generate the response of the system to an initial perturbation is the ability to calculate the physical forcing terms in the fundamental equations, in this case absorption of radiation by gases in the equation for conservation of energy.

Human choice

In contrast, economic principles do not yield fully closed sets of equations. Key relationships are 'behavioural', that is they represent processes subject to human choice. The functional forms and parameter values of behavioural equations cannot be derived from available theory. The generally accepted principles of economics, such as the laws of supply and demand, simply provide guidelines. For example, the law of demand implies that the demand for electricity is negatively related to its price and positively related to the prices of alternative energy sources. The quantitative functional form of these relationships cannot be derived directly from the principles.

In economic models, the completion of the specification of the equations — the functional form, the operational definitions of the variables and the values of the coefficients of the variables — is typically based on empirical data. The choice among the (perhaps infinite) universe of specifications that are consistent both with the economic principles and the data set available is made according to a conventional set of decision rules. Often the data are assumed to exhibit a specific pattern of random deviation from an otherwise deterministic relationship, so that statistical criteria can be used to derive and evaluate alternative specifications. This is the approach associated with 'econometric' modelling. Sometimes the data are used to obtain average values, or ranges of average values, of the coefficients of first- or second-order variables in linear equations. This approach is broadly descriptive of input–output, linear programming and systems dynamics models. In general, then, economic theory may suggest the direction (that is the algebraic sign) of a change in a behavioural variable (peak seasonal use of electricity, for example) in response to a change in conditions, but not the size of the response or the functional form of the equation, which have to be generated from data.

The importance of the role played by first principles in climate models should not be exaggerated, however. In atmospheric models, many of the physical forc-

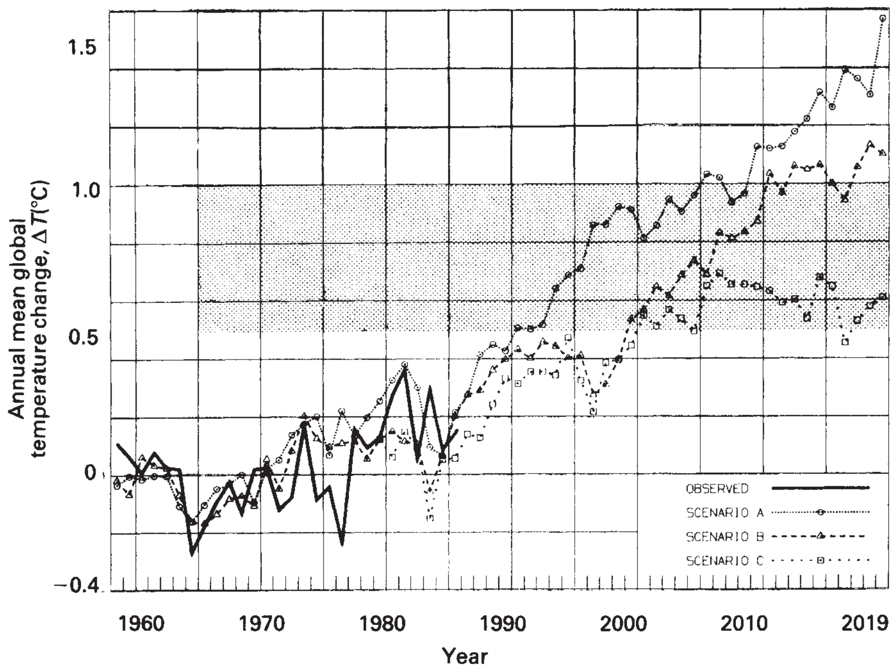

Fig. 1 Annual mean global surface air temperature change computed in the Goddard Institute for Space Sciences general circulation model for three different scenarios of trace gas growth[9] (A assumes current growth rates of trace gas emissions; B assumes decreasing growth rates; C assumes no trace gas increase after the year 2000). Observational data is from Hansen and Lebedeff[10]. The shaded range is an estimate of global temperature during the peak of the current and previous interglacial periods, about 6,000 and 120,000 years before present, respectively. The zero point for observations is the 1951–1980 mean[10]; the zero point for the model is the control run mean, with 1958 trace gas concentrations. The results show how sensitive predictions of future temperatures are to the future releases of trace gases and thus to the future economy.

ing terms (for example, turbulent fluxes) are imperfectly known, and this is even more true in representations of other components of the climate system, such as the ground hydrology and oceans. Therefore climate modellers also have to choose the functional relationships of various processes by reference to observations. In the physical sciences, controlled experiments, in which only one parameter is allowed to vary at a time, can often be conducted to derive the functional relationships; thus atmospheric modellers can carry out experiments in some cases (for example, determining absorption spectra of atmospheric gases). But this cannot be done generally, for it is impossible to hold climate variables fixed in the open physical system of the real world.

In economics, as in the other social sciences, controlled experiments are difficult, either because the variables cannot be controlled or because it is prohibitively expensive to do so. Thus, although basic principles and, to a lesser extent, controlled experiments are sources of specific formulations for climate models but not for economic models, both ultimately contain functional relationships derived from uncontrolled observations. Furthermore, the necessary reliance on observations raises the possibility that both models are 'tuned to' (that is, biased in favour of) the current situation.

Spatial scales in climate models are determined by the 'grid' over which the model calculations are made, generally in the order of 10^4–10^6 km^2. 'Sub-grid' scale processes are incorporated in parameterized form, based on field measurements or mesoscale models, while larger scales are all explicitly represented in the continuous global model. Although there are different models for different scales, climate and climate change are global phenomena involving energy transport from one region to another, and must be addressed with global models.

Economic models, instead of using gridded spatial dimensions, are organized in terms of scales of economic activity. The equations of microeconomic models represent the activity of an individual agent (buyer or seller), a group of agents (for instance, electrical utilities), a market (supply and demand for electricity) or a sector (energy). Macroeconomic models represent activity at higher levels of aggregation, defined in terms of an appropriate geopolitical unit (county, state, country, groups of countries), a unit of collective decision-making. Economic data (and thus model validation) tend to be reported in geopolitical units, rather than in uniform geographical scales. In assessing the impact of climate change, the microeconomic approach is necessary for studying the direct effects at the point of contact between climate change and economic processes, but the macroeconomic approach is needed for evaluating overall costs and benefits within the geopolitical area of relevance to policymakers.

Economists use very different models for different time-scales, reflecting their belief that the effects of some variables are more important in the short term but are dominated by the effects of other variables in the long term. Short-term macroeconomic models, which simulate quarterly changes over a period of about three years, involve financial variables such as money supply, short-term interest rates and consumer credit, as well as changes in inventories and profits. The model-builder's objective is to track cyclical fluctuations in production, income, employment and spending. These models are usually incapable of generating cycles beyond a single turning point, such as the end of a recession, and tend to diverge, producing exaggerated, unrealistic results if run over long periods.

Longer-term economic models employ a completely different set of variables: demographics, capital accumulation, the consumption of natural resources and technological change. They are used to simulate annual changes over periods from five years to several decades and provide the basis for strategic planning decisions.

In theory, atmospheric models can be used for both short-term weather forecasting (days to weeks), or longer-term climate projections. The same fundamental set of equations applies regardless of time-scale, because climate is simply the time-averaged weather. Additional physical processes become important on time-scales of years to decades, such as the transport of heat through the bottom of the oceanic mixed layer or the effect of changing vegetation. Other components of the system, such as ice sheets, influence climate on time-scales of centuries to millennia. Representations of these effects must be included in climate models when relevant, so climate modelling involves additional scientific disciplines compared to weather forecasting. But such processes still act on the primary atmospheric variables of temperature, pressure, wind and moisture, which are the same regardless of length of time of integration.

Time and space

In practice, however, weather-forecasting models are never used for long-term climate studies, nor are climate models used for short-term predictions. Weather-forecasting models are run with much finer spatial scales to guarantee proper movement of weather systems. In order to minimize the time it takes to produce forecasts, these models do not include processes which act too slowly to influence weather. They thus often lack the requisite physics for long-term integrations, and their numerical schemes do not necessarily conserve fundamental quantities such as mass and energy. In some cases, they too will diverge if run for a long time. On the other hand, the general circulation climate models are integrated for up to one hundred model years and are developed on coarse spatial scales. When run with finer resolution they eventually develop excessive winds, presumably due to the parameterization of processes not fully understood. Both climate and economic models are thus developed for and tuned to specified time and space horizons.

Forecasting

Climate and economic modellers have somewhat different forecasting methods. A climate model, like most physically based models, provides a single-valued solution when posed a specific problem; that is, one climate forcing function (such as CO_2 concentration) is changed and the model provides a specific 'forecast' of the other internal climate characteristics (temperature, precipitation and so on). The important variables which are not predicted and have to be specified, such as solar radiation, are thought to be limited in number.

Economic models tend to contain a greater number of important variables whose values are not determined, and therefore need to be pre-specified. In a macroeconomic model, these variables usually represent policy decisions, such as the level of government spending or the growth rate of the money supply. In a microeconomic model, they usually represent variables that would be determined at a higher level of aggregation, such as the world price of wheat in a regional agricultural model. So each model simulation requires assumptions to be made about the variables whose future values are exogenous (external) to the model, and economic models thus produce results which are often cast in terms of probability solution sets. Actually, both climate models and economic models produce ranges of results: given the uncertainties in projected emissions of trace gases (which depend upon economic factors[6]), there are many alternative climate-change scenarios, each producing a specific forecast for use in economic assessments, with each forecast then leading to a probability distribution of economic model output.

What is the current status of the different forecasting disciplines, and how much confidence can we place in their predictions? If the use of empirical relationships implies that climate and economic models are biased towards representing current conditions, then there is a fundamental question regarding their accuracy when venturing into the future. The rapid warming predicted for the coming decades is outside the range of historical experience. It is possible that both the climate and economic systems will exhibit at least some interactions not included in current calculations. A prime candidate on the climate side is the possible variation of cloud optical thickness as climate warms, which can greatly affect the degree of warming. On the economic side, the relationship between electrical demand and temperature might change, especially if temperatures reach levels not previously experienced.

To compare the climate model's sensitivity to that of the real world, two approaches have been used. One is to estimate how temperature has changed over the past century, and then to compare that (relatively small) change to the strength of the probable climate forcing mechanisms[7]. This procedure has led to the view that climate models can predict future global temperature changes from a doubling of atmospheric CO_2 to within about a factor of two. It cannot yet provide a more precise evaluation because of uncertainties in our understanding of ocean heat uptake. This same uncertainty prevents us from firmly establishing the *rate* of future climate change. The second approach, used in assessing the climate model's suitability for evaluating large climate changes, is through the simulation of palaeoclimates, such as the last Ice Age. Although the models have produced the proper degree of cooling in the extratropics, the results are strongly constrained by the Ice Age boundary conditions of land-ice and sea-surface temperatures which are used as inputs. Even under these conditions, there are first-order uncertainties in the amount of cooling at low latitudes[8]. It is not known whether the models can realistically portray the entrance into or exit from an Ice Age, because the very long time integrations required (thousands of years) make the project unfeasible. Furthermore, climate models lack the necessary glacial dynamics.

Thus, confidence in our ability to model large climate changes (in the order of the 4 °C global cooling of the Ice Age or the comparable warming of an atmosphere with a doubled level of CO_2) lies in our assessment of the approximate climate sensitivity, and in our expectation (or hope) that we understand the physical principles which dominate within the expected range of mean temperatures. Of more dubious quality are regional and local forecasts of climate change, especially forecasts of the changes in the hydrological cycle (precipitation, soil moisture and so on) which depend upon the crudely modelled physics of convection and ground hydrology. Nevertheless, for climate models, there is widespread conviction that the basic uncertainties are solvable, so that models and predictions should improve with time.

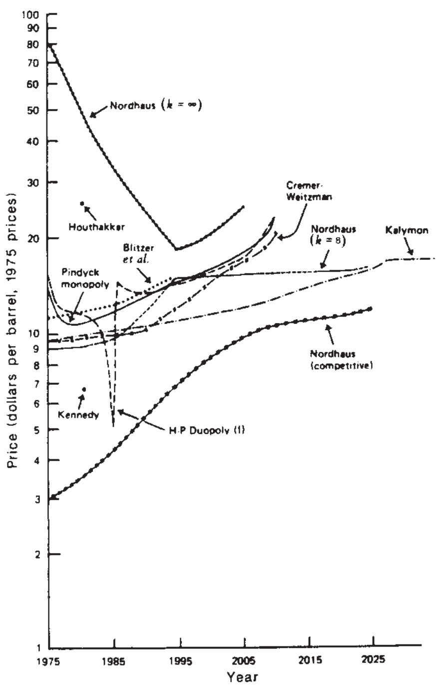

Fig. 2 Estimates of the time path of the price of oil, made between 1975 and 1977, from economic models with differing assumptions about OPEC pricing policies[11]. The pricing policies include maximization of monopoly profits, maximization of the cartel's total revenue, and maintenance of members' production shares. The bottom curve estimates the competitive market price in the absence of a cartel. The figure illustrates the uncertainty in economic forecasts due to unpredictable policy behaviour, as well as the ability of economic models to simulate a range of alternative scenarios.

Economic modellers did not predict the rapid rise in oil prices during the 1970s and thus its global consequences. Yet this failure arose not because the natural resource was limited, which could have been predicted, but from unforeseen political decisions. In fact, OPEC policy-making continues to create uncertainty about the future path of energy costs (see Fig. 2). This example highlights what can and cannot be expected from economic forecasting models. Characteristics of the economic system which are already in evidence, such as the distribution of natural resources or well-established behavioural tendencies, may be expected to influence economies in the future and their reaction to climate change. Long-term forecasting models should be able to calculate potential interactions among these components. Political decisions, however, will remain unpredictable, although the direction and relative scale of the effects of different policies can be estimated.

All economic decisions are made in a technological context. A given state of technology allows economic agents a specific range of choices. This increases the difficulty of predicting average behaviour, but defines the extent of possible variations. Over time, however, technology itself is subject to change, as society adjusts to limitations on the quantity and use of resources by inventing new resources or new ways to use existing resources more efficiently. Technological change has become such an expected response to scarcity or potential gains that many economic models embody some form of induced innovation in their equations. However, very few such models actually provide a framework for defining and analysing alternative technologies of the future.

Absence of links

One of the main problems with the joint application of climate and economic models is the absence of links, that is, processes and variables common to both types of model. Although the forecasting models run by crop producers or electrical utilities contain climate variables, most policy-orientated models do not. To some extent this is because data are often not available on the sensitivity of economic processes to climate. The information that does exist usually relates to extreme weather events, such as droughts or floods, which are followed by a return to normal conditions. As climate change represents a long-term shift away from the mean, and no such shift has occurred during the modern technological era, there simply aren't any relevant data.

Physical process models are now being used as intermediate steps between climate and economic models. These models, such as dynamic process crop growth models and watershed hydrological models, estimate the effects of climate changes on variables of economic interest, such as wheat yield or water availability. Changes in these variables generated by the process models are then used as inputs in economic models. The physical process models are useful because they provide detailed responses of the modelled system to climate change, but they are cumbersome as linkages because they must be rerun for each possible scenario. Another problem is that they require climatic variables on scales smaller than the climate model's resolved grid. Process models are available for only certain aspects of the economy, particularly agriculture, forestry and water resources. Models of other potentially sensitive processes, such as demographic response to climate change, do not exist because of lack of data.

Furthermore, without the use of aggregated macroeconomic models, the full scale of economic interaction and consequence cannot be evaluated. The effects of climate change will probably ricochet through the economy, and assessments based on keeping most aspects constant are unlikely to be correct in the long run. The situation is very similar to that of the climate analysis itself: the feedbacks of the physical system provide the greater part of the warming effect of increased CO_2 on climate.

Given the current status of the different models and their linkages, what are the improvements needed to increase our ability to evaluate the economic effects of climate change? Climate modellers must improve regional forecast accuracy, by including more realistic ocean and ground hydrology along with improved parameterizations of clouds and convection in their models. Better ocean models will require many additional observations of ocean processes, and funding agencies must provide support for group ocean-modelling efforts.

Economic models must include explicit climate-sensitive functions. Intermediate physical process models, when appropriate, should generate response surfaces to specify these relationships. Additional research on the often subtle dependence of human society on climate is needed.

There is a need to design macroeconomic models specifically to assess the aggregate economic effect of global climate change. For this purpose economists should adopt a customized approach to aggregating markets and groups of economic agents, explicitly including utilities and other activities such as agriculture, forestry, fishing and recreation which are known to respond directly to climate variables.

The spatial mismatch between geometric grids in climate models and geopolitical grids in economic models must be overcome. We need to generate geographical databases of economic information (for example urban, rural, industrial and agricultural identifiers) that are consistent with the gridbox resolutions of climate models, while recognizing the transport mechanisms that disperse the product throughout the economy. Physical process models should be developed for larger scales, consistent with the resolution of the climate model. And climate modellers should attempt to use as fine a spatial resolution as is practical. This would provide results on more appropriate spatial scales, which one could then aggregate to maintain the integrity of geopolitical units.

Improving the linkages will require interdisciplinary research by physical scientists and economists, as has been done in studies of energy and oil markets. In the academic world, one department ideally suited to the purpose is geography, which overlaps both physical and social sciences. In this regard, the recent trend towards phasing out geography departments at Ivy League universities may well be short-sighted.

For time-scales extending into the middle of the next century, the relationships between the economy (particularly greenhouse gas release) and climate will be interactive. At present, the only possible way to incorporate this relationship in studies of climate change is to iterate solutions of the separate models. It would be useful to start work upon a global climate–economic model. Given the flexibility of economic models, the best approach would be to build an economic model into the framework of the climate model. The resulting joint model could be employed at this stage to explore the basic dynamic properties of the systems and to establish ranges of parameters. It could then be determined which economic sectors are most sensitive to climate change and thus need to be modelled in greater detail.

In the foreseeable future, we are unlikely to be able to develop models to predict extreme events such as calamities of last October or the effect of the OPEC oil boycott on oil prices in the 1970s. Even prediction of the long-term changes may be beyond our ability, if unforeseen extreme events (such as war) occur. Thus programmes devoted to research into the economic effects of climate change should not be expected to provide bottom-line assessments of cost. The proper use of such models is to run alternative simulations and investigate potential magnitudes of total costs, relative gains and losses, and possible courses of action to minimize disruption or maximize opportunity.

Frank assessment

A frank assessment of the (lack of) speed with which progress in this area is occurring leads to the conclusion that it is very possible that a dramatic change in climate will arrive before any adequate assessments of its economic effects become available. To make matters worse, climate change will be a continuing phenomenon, so adjustments made in one decade may well be inappropriate in the next. There is a great deal of work to be done by modellers of both persuasions if we are to be in a position to prepare for, instead of simply react to, climate change. □

1. Andresen, J. *Wkly Weath. Crop Bull.* **74**, 19 (1987).
2. Taub, A.H. *John von Neumann Collected Works, Vol. VI* (Pergamon Press, New York, 1963).
3. Charney, J. *Carbon Dioxide and Climate: A Scientific Assessment* (National Academy Press, Washington, DC, 1979).
4. Smagorinsky, J. *Carbon Dioxide and Climate: A Second Assessment* (National Academy Press, Washington, DC, 1982)
5. World Meteorological Organization *WMO Bulletin* **35**, 130–134 (1986).
6. Nordhaus, W. *AEA Papers and Proceedings* **72**, 242–246 (1982).
7. Hansen, J. *et al. Science* **213**, 957–966 (1981).
8. Rind, D. & Peteet, D. *Quaternary Res.* **24**, 1–22 (1985).
9. Hansen, J. *et al. J. geophys. Res.* **93** (1988, in the press).
10. Hansen, J. & Lebedeff, S. *J. geophys. Res.* **92**, 13,345–13,372 (1987).
11. Nordhaus, W. *The Efficient Use of Energy Resources* (Yale University Press, New Haven, 1979).

David Rind is at NASA/Goddard Space Flight Center, Institute for Space Studies, New York, New York 10025, USA. Arthur Rosenzweig is at Civitech Corporation, New York, and Cynthia Rosenzweig is at the Department of Geography, Columbia University, New York, and the Goddard Institute for Space Studies.